

## **“A NOVEL TECHNIQUE THAT MAXIMIZES ERGODIC AND OUTAGE CAPACITY FOR ENHANCED SPECTRUM SHARING IN COGNITIVE RADIO NETWORK”**

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### **ABSTRACT**

Cognitive Radio technology helps in designing wireless system for efficient deployment of radio spectrum with its sensing technique, self-adaptation and spectrum sharing. Spectrum sharing is an effective method of alleviating the scarcity of radio spectrum problem by allowing unlicensed users (secondary users) to coexist with licensed users (primary users) under the condition of protecting the later from harmful interference. In this paper, we emphasis on the throughput maximization of spectrum sharing cognitive radio networks and propose an innovative cognitive radio system that will significantly improve their achievable throughput more specifically, a novel receiver and a frame structure for spectrum sharing is introduced. The problem of optimal power allocation strategy that maximizes the ergodic capacity of the system under average transmit and interference power constraints along with the problem of optimal power allocation strategy that maximizes the outage capacity of the system under average transmit, peak interference and interference power constraints is also studied. The simulation results will demonstrate the improved outage capacity achieved by the proposed cognitive radio system in comparison with conventional spectrum sharing cognitive radio systems under various power constraints.

**KEYWORDS:** Cognitive Radio, Optimal Power Allocation, Spectrum Sharing, Throughput Maximization, Outage Capacity

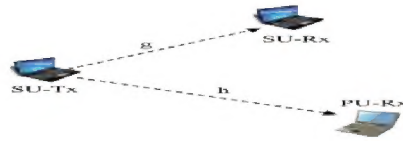
### **INTRODUCTION**

A recent survey of spectrum utilization made by the Federal Communications Commission (FCC) has indicated that the current fixed spectrum allocation policy has resulted in several bands being severely underutilized both in temporal and spatial manner [1], the actual licensed spectrum is largely underutilized in vast temporal and geographic dimensions. To solve the problem of spectrum scarcity and spectrum underutilization, the use of CR technology [2], [3] is being considered because of its ability to rapidly and autonomously adapt operating parameters to changing requirements, conditions and eliminate the spectrum scarcity problem and support the increasing demand for wireless communications by allowing unlicensed (secondary) users to access licensed frequency bands, under the condition of protecting the quality of service (QoS) of the licensed (primary) networks. Cognitive radio (CR), as an agile radio technology, has been proposed to promote the efficient use of the spectrum.

### **Proposed Approach**

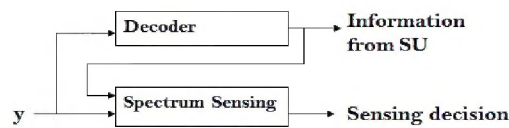
In the cognitive radio system presented in Figure 1 let  $g$  and  $h$  (ergodic, stationary) denote the instantaneous channel power gains from the secondary transmitter (SU-Tx) to the secondary receiver (SU-Rx) and the primary receiver (PU-Rx), respectively. In the following, it is described how the proposed spectrum sharing scheme operates and present the receiver and frame structure employed in this cognitive radio system. In practice, the channel power gain  $h$  can be obtained

via, e.g., estimating the received signal power from the PU-Rx when it transmits, under the assumptions of the pre-knowledge on the PU-Rx transmit power level and the channel reciprocity.



**Figure 1: System Model**

### Receiver Structure



**Figure 2: Receiver Structure of the Proposed Cognitive Radio System**

The receiver structure of the proposed cognitive radio system is presented in Figure 2. The received signal at the secondary receiver is given by

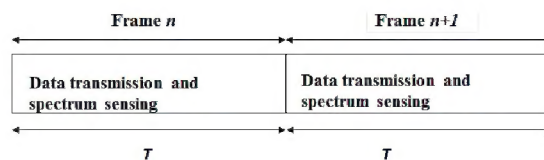
$$y = \theta x_p + x_s + n \quad (1)$$

Where  $\theta$  denotes the actual status of the frequency band ( $\theta = 1$  if the frequency band is active, whereas  $\theta = 0$  if the frequency band is idle),  $x_p$  and  $x_s$  represent the received signal from the primary users and the secondary transmitter, respectively. Finally,  $n$  denotes the additive noise. The received signal  $y$  is initially passed through the decoder, as depicted in Figure 2, where the signal from the secondary transmitter is obtained. In the following, the signal from the secondary transmitter is cancelled out from the aggregate received signal  $y$  and the remaining signal

$$y = \theta x_p + n \quad (2)$$

Is used to perform spectrum sensing. As a result, instead of using a limited amount of time  $\tau$  almost the whole duration of the frame  $T$  can be used for spectrum sensing under the proposed cognitive radio system. This way, we are able to perform spectrum sensing and data transmission at the same time and therefore maximize the duration of both. In the receiver facilitates the use of more complex spectrum sensing techniques that exhibit increased spectrum sensing capabilities, but require higher sensing time (such as cyclostationary detection, Generalized Likelihood Ratio Test (GLRT) - based or covariance-based spectrum sensing techniques), which prohibits their application for quick periodical spectrum sensing under the frame structure.

### Frame Structure



**Figure 3: Frame Structure of the Proposed Cognitive Radio System**

The frame structure of the proposed cognitive radio system presented in Figure 3 both spectrum sensing and data transmission are performed at the same time using the receiver structure as discussed earlier. The advantage of the

proposed frame structure is that the spectrum sensing and data transmission times are simultaneously maximized. The increased sensing time enables the detection of very weak signals from the primary users thus reducing false alarm probability that would significantly remove discontinuity hence increasing the throughput of the cognitive radio system. Using the proposed frame structure leads to an improved detection probability, thus better protection of the primary users from harmful interference which enables a better use of the available unused spectrum. The false alarm prevents the secondary users from accessing an idle frequency band using higher transmit power, and therefore limits their throughput as per requirement. The continuous spectrum sensing can be achieved under the proposed cognitive radio system, which ensures better protection of the primary networks.

### Ergodic Capacity of Proposed Spectrum Sharing Scheme

In this section, the problem of deriving the optimal power allocation strategy that maximizes the ergodic capacity of the cognitive radio network that operates under the proposed spectrum sharing scheme is discussed. In the proposed cognitive radio system, the secondary users adapt their transmit power at the end of each frame based on the decision of spectrum sensing, and transmit using higher power  $P_0$  when the frequency band is detected to be idle and lower power  $P_1$  when it is detected to be active. Following the approach of [6], [12], [17], the instantaneous transmission rates when the frequency band is idle ( $H_0$ ) and active ( $H_1$ ) are given by

$$\begin{aligned} r_0 &= \log_2 \left( 1 + \frac{gP_0}{\sigma_n^2} \right) \\ r_1 &= \log_2 \left( 1 + \frac{gP_1}{\sigma_n^2 + \sigma_p^2} \right) \end{aligned} \quad (3)$$

Respectively, where  $\sigma_p^2$  denotes the received power from the primary users. The latter parameter restricts the achievable throughput of all spectrum sharing cognitive radio network and indicates the importance of spectrum sensing and optimal power allocation on the throughput maximization of spectrum sharing cognitive radio networks. However, the perfect spectrum sensing may not be achievable in practice, where the actual status of the primary users might be falsely detected. Therefore, the four different cases of instantaneous transmission rates based on the actual status of the primary users (active/idle) and the decision of the secondary users (primary user present/absent) as follows:

$$\begin{aligned} r_{00} &= \log_2 \left( 1 + \frac{gP_0}{\sigma_n^2} \right) \\ r_{01} &= \log_2 \left( 1 + \frac{gP_1}{\sigma_n^2} \right) \\ r_{10} &= \log_2 \left( 1 + \frac{gP_0}{\sigma_n^2 + \sigma_p^2} \right) \\ r_{11} &= \log_2 \left( 1 + \frac{gP_1}{\sigma_n^2 + \sigma_p^2} \right) \end{aligned} \quad (4)$$

Here, the first index number of the instantaneous transmission rates indicates the actual status of the primary users (“0” for idle, “1” for active) and the second index number, the decision made by the secondary users (“0” for absent, “1” for present) In order to keep the long-term power budget and effectively protect the primary users from harmful interference, we consider an average (over all fading states) transmit and interference power constraint that can be formulated as follows:

$$E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1 - P_d)P_0 + P(H_1)P_dP_1\} \leq P_{av}$$

$$E_{g,h}\{P(H_1)(1 - P_d)hP_0 + P(H_1)P_dhP_1\} \leq \Gamma \quad (5)$$

where  $P(H_0)$  and  $P(H_1)$  denote the probability that the frequency band is idle and active, respectively,  $P_d$  and  $P_{fa}$  represent the detection and false alarm probability, respectively, whereas  $P_{av}$  denotes the maximum average transmit power of the secondary users, and  $\Gamma$  the maximum average interference power that is tolerable by the primary users. The reason for choosing an average interference power constraint is based on the results in [13] and [18], which indicate that an average interference power constraint leads to higher ergodic throughput for the cognitive radio system, and provides better protection for the primary users compared to a peak interference power constraint. Finally, the optimization problem that maximizes the ergodic throughput of the proposed spectrum sharing cognitive radio system under joint average transmit and interference power constraints can be formulated as follows:

$$\text{maximize } C = E_{g,h}\{P(H_1)P_d r_{11} + P(H_0)P_{fa} r_{01} + P(H_1)(1 - P_d) r_{10} + P(H_0)(1 - P_{fa}) r_{00}\} \quad (6)$$

subject to (4), (5),  $P_0 \geq 0$ ,  $P_1 \geq 0$ . (6)

The Lagrangian with respect to the transmit powers  $P_0$  and  $P_1$  is given by

$$L(P_0, P_1, \lambda, \mu) = E_{g,h}\{P(H_1)P_d r_{11} + P(H_0)P_{fa} r_{01} + P(H_1)(1 - P_d) r_{10} + P(H_0)(1 - P_{fa}) r_{00}\} - \lambda E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1 - P_d)P_0 + P(H_1)P_dP_1\} + \lambda P_{av} - \mu E_{g,h}\{P(H_1)(1 - P_d)hP_0 + P(H_1)P_dhP_1\} + \mu \Gamma \quad (7)$$

Whereas the dual function can be obtained by

$$d(\lambda, \mu) = \sup L(P_0, P_1, \lambda, \mu) \quad (8)$$

In order to calculate the dual function  $d(\lambda, \mu)$ , the supremum of the Lagrangian with respect to the transmit powers  $P_0$  and

$P_1$  needs to be obtained. We therefore apply the primal-dual decomposition method [19], which facilitates the solution of the joint optimization problem by decomposing it into two convex single-variable optimization problems, one for each of the transmit powers  $P_0$  and  $P_1$ , as follows:

#### Sub Problem 1

Maximize

$$\{P_0 \geq 0\}$$

$$f_1(P_0) = E_{g,h}\{P(H_1)(1 - P_d) \log_2(1 + \frac{gP_0}{\sigma_n^2 + \sigma_p^2}) + P(H_0)(1 - P_{fa}) \log_2(1 + \frac{gP_0}{\sigma_n^2})\} - \lambda E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_1)(1 - P_d)P_0\} - \mu E_{g,h}\{P(H_1)(1 - P_d)hP_0\} \quad (9)$$

#### Sub Problem 2

Maximize

$$\{P_1 \geq 0\}$$

$$f_2 = E_{g,h} \{ P(H_0)(P_{fa}) \log_2(1 + \frac{gP_1}{\sigma_n^2}) + P(H_1)(P_d) \log_2(1 + \frac{gP_0}{\sigma_n^2 + \sigma_p^2}) \} - \lambda E_{g,h} \{ P(H_0)(P_{fa})P_1 + P(H_1)(P_d)P_1 \} - \mu E_{g,h} \{ P(H_1)(P_d)hP_1 \} \quad (10)$$

After forming their Lagrangian functions and applying the Karush–Kuhn–Tucker (KKT) conditions, the optimal powers  $P_0$  and  $P_1$  for given  $\lambda, \mu$  are given by

$$P_0 = \left[ \frac{A_0 + \sqrt{\Delta_0}}{2} \right] \\ P_1 = \left[ \frac{A_1 + \sqrt{\Delta_1}}{2} \right] \quad (11)$$

where  $[x]^+$  denotes  $\max(0, x)$

$$A_0 = \frac{\log_2(e)(\alpha_0 + \beta_0)}{\lambda(\alpha_0 + \beta_0) + \mu\beta_0 h} - \frac{2\sigma_n^2 + \sigma_p^2}{g} \\ \Delta_0 = A_0^2 - \frac{4}{g} \left\{ \frac{\sigma_n^2 + \sigma_p^2}{g\sigma_n^{-2}} - \frac{\log_2(e)(\alpha_0(\sigma_n^2 + \sigma_p^2) + \beta_0\sigma_n^2)}{\lambda(\alpha_0 + \beta_0) + \mu\beta_0 h} \right\} \\ A_1 = \frac{\log_2(e)(\alpha_1 + \beta_1)}{\lambda(\alpha_1 + \beta_1) + \mu\beta_1 h} - \frac{2\sigma_n^2 + \sigma_p^2}{g} \\ \Delta_1 = A_1^2 - \frac{4}{g} \left\{ \frac{\sigma_n^2 + \sigma_p^2}{g\sigma_n^{-2}} - \frac{\log_2(e)(\alpha_1(\sigma_n^2 + \sigma_p^2) + \beta_1\sigma_n^2)}{\lambda(\alpha_1 + \beta_1) + \mu\beta_1 h} \right\}$$

and the parameters in above equations are given by

$$\alpha_0 = P(H_0)(1 - P_{fa}) \\ \beta_0 = P(H_1)(1 - P_d) \\ \alpha_1 = P(H_0)(P_{fa}) \\ \beta_1 = P(H_1)(P_d) \quad (12)$$

### Outage Capacity of Proposed Spectrum Sharing Scheme

The ergodic capacity is used for fast fading channels or delay-insensitive applications [21], whereas for slow fading channels or delay-sensitive applications, such as voice and video transmission, the outage capacity [21], [22] comprises a more appropriate metric for the capacity of the system. The outage capacity  $C_{out}$  is defined as the highest transmission rate that can be achieved by the communications system with the probability of outage under a maximum value. In this section the outage capacity of the proposed spectrum sharing cognitive radio system is studied and the power allocation strategy for a combination of different constraint on the outage capacity is derived that include average transmit power constraints, average interference power constraints and peak interference power constraints. For power allocation the truncated channel inversion with fixed rate (TIFR) technique is considered, where the secondary transmitter uses the channel side information (CSI) to invert the channel fading, in order to achieve a constant signal-to-noise ratio (SNR) at the secondary receiver during the periods when the channels fade above a certain “cutoff” value. This adaptive transmission scheme offers the advantage of non-zero achievable rates for a target outage probability

$P_{out} = \overline{P_{out}}$ , even when the fading is extremely severe such as in Rayleigh fading cases, where a constant transmission rate cannot be achieved under all fading states of the channel.

### Outage Capacity under Average Transmit and Interference Power Constraints

These can be formulated as follows:

$$E_{g,h}\{P(H_0)(1 - P_{fa})P_0 + P(H_0)P_{fa}P_1 + P(H_1)(1 - P_d)P_0 + P(H_1)P_dP_1\} \leq P_{av} \quad (13)$$

$$E_{g,h}\{P(H_1)(1 - P_d)hP_0 + P(H_1)P_dhP_1\} \leq \Gamma \quad (14)$$

As mentioned in the beginning of this section, in the TIFR technique the secondary transmitter inverts the channel fading, in order to achieve a constant rate at the secondary receiver when the channel fading is higher than a “cutoff” threshold. We define here this cutoff threshold by  $\gamma_0$  when the primary users are detected to be idle and by  $\gamma_1$  when the primary users are detected to be active. The transmit power in both cases is suspended when the link  $g$  between the secondary transmitter and the respective receiver is weak compared to the interference channel  $h$  from the secondary transmitter to the primary receiver. Considering here the same metric, i.e.  $h/g$ , for the case that the primary users are detected to be idle, namely for  $P_0(g, h)$  so that to effectively protect the primary users from harmful interference when a miss-detection occurs. Based on the average interference power constraint (13), the average transmit power constraint (14) the parameter  $\alpha$  should satisfy the following constraints:

$$\alpha = \Gamma \cdot \{P(H_1)(1 - P_d)[\log(1 + \frac{\gamma_0}{\sigma^2}) - \frac{\gamma_0}{\gamma_0 + \sigma^2}] P(H_1)(P_d)[\log(1 + \frac{\gamma_1}{\sigma^2}) - \frac{\gamma_1}{\gamma_1 + \sigma^2}]\}^{-1} = t_1(\gamma_0, \gamma_1) \quad (15)$$

$$\alpha \leq \frac{P_{av}}{K_0 \log(1 + \frac{\gamma_0}{\sigma^2}) + K_1 \log(1 + \frac{\gamma_1}{\sigma^2})} = t_2(\gamma_0, \gamma_1) \quad (16)$$

Where the parameters  $K_0$  and  $K_1$  are given by

$$K_0 = P(H_0)(1 - P_{fa}) + P(H_1)(1 - P_d) \quad (17)$$

$$K_1 = P(H_0)(P_{fa}) + P(H_1)(P_d) \quad (18)$$

Therefore, the channel capacity under the TIFR policy can be obtained as follows:

$$C_{TIFR} = \max_{\gamma_0, \gamma_1} \left\{ \log(1 + \frac{1}{\sigma^2} \min\{t_1(\gamma_0, \gamma_1), t_2(\gamma_0, \gamma_1)\}) \cdot (1 - \frac{K_0 \sigma^2}{\gamma_0 + \sigma^2} - \frac{K_1 \sigma^2}{\gamma_1 + \sigma^2}) \right\} \quad (19)$$

Where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$  and  $\gamma_1$ .

Finally the outage capacity of the proposed spectrum sharing cognitive radio network under joint average transmit and interference power constraints is given by,

$$C_{out} = \max_{\gamma_0} \{ \log(1 + \frac{1}{\sigma^2} \min\{\bar{t}_1(\gamma_0), \bar{t}_2(\gamma_0)\}) \cdot (1 - \overline{P_{out}}) \} \quad (20)$$

where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$ .

### Outage Capacity under Both Average and Peak

#### Interference Power Constraints

The aforementioned constraints can be formulated as follows:

$$E_{g,h}\{P(H_1)(1 - P_d)hP_0(g, h) + P(H_1)P_dhP_1(g, h)\} \leq \Gamma \quad (21)$$

$$P(H_1)(1 - P_d)hP_0(g, h) \leq Q_{peak} \quad (22)$$

$$P(H_1)P_dhP_1(g, h) \leq Q_{peak} \quad (23)$$

where we have considered the interference caused under both cases, namely when the frequency band is correctly detected to be active and falsely detected to be idle. Based on the average interference power constraint (21), the peak interference power constraints (22) and (23), and the parameter  $\alpha$  should satisfy the following constraints:

$$\alpha = \frac{1}{P(H_1)} \cdot \left\{ (1 - P_d) \left[ \log \left( 1 + \frac{\gamma_0}{\sigma^2} \right) - \frac{\gamma_0}{\gamma_0 + \sigma^2} \right] + (P_d) \left[ \log \left( 1 + \frac{\gamma_1}{\sigma^2} \right) - \frac{\gamma_1}{\gamma_1 + \sigma^2} \right] \right\}^{-1} = q_1(\gamma_0, \gamma_1) \quad (24)$$

$$\alpha \leq \frac{Q_{peak}\sigma^2}{P(H_1)(1-P_d)\gamma_0} = q_2(\gamma_0) \quad (25)$$

$$\alpha \leq \frac{Q_{peak}\sigma^2}{P(H_1)P_d\gamma_1} = q_3(\gamma_1) \quad (26)$$

Therefore, the maximum capacity under the

TIFR transmission policy can be obtained as follows:

$$C_{TIFR} = \max_{\gamma_0, \gamma_1} \left\{ \log \left( 1 + \frac{\min \{q_1(\gamma_0, \gamma_1), q_2(\gamma_0), q_3(\gamma_1)\}}{\sigma^2} \right) \cdot \left( 1 - \frac{K_0\sigma^2}{\gamma_0 + \sigma^2} - \frac{K_1\sigma^2}{\gamma_1 + \sigma^2} \right) \right\} \quad (27)$$

where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$  and  $\gamma_1$ . Therefore the outage capacity is given by

$$C_{out} = \max_{\gamma_0} \left\{ \log \left( 1 + \frac{\min \{q_1(\gamma_0), q_2(\gamma_0), q_3(\gamma_0)\}}{\sigma^2} \right) \cdot (1 - \overline{P_{out}}) \right\} \quad (28)$$

where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$ .

### Outage Capacity under Average Transmit and Interference Power Constraints with High Target Detection Probability

We consider now the case that a high target detection probability  $P_d$  is employed on the proposed spectrum sharing cognitive radio system, and that when the primary users are detected to be idle, the secondary transmitter accesses the frequency band in an opportunistic spectrum access manner, and namely it does not impose an interference power constraint. In this case, the average transmit and interference power constraint take the following form:

$$E_{g,h}\{\bar{K}_0P_0 + \bar{K}_1P_1\} \leq P_{av} \quad (29)$$

$$E_{g,h}\{P(H_1)(\bar{P}_d)hP_1(g, h)\} \leq \Gamma \quad (30)$$

respectively, where  $K_0$  and  $K_1$  are given by (17) and (18)

The transmit power  $P_0$  (when the primary users are detected to be idle) depends only on the channel  $g$  between the secondary transmitter and the respective receiver, and is independent of the interference channel  $h$  to the primary receiver.

Based on the average transmit power constraint (29), the average interference power constraint (30), the parameter  $\alpha$  should satisfy the following constraints

$$\alpha = \frac{\Gamma}{P(H_1)(\overline{P_d}) \log\left(1 + \frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1 + \sigma^2}} = u_1(\gamma_1) \quad (31)$$

$$\alpha \leq \frac{P_{av}}{\overline{K_0} E\left(\frac{\gamma_0}{\sigma^2}\right) + \overline{K_1} \log\left(1 + \frac{\gamma_1}{\sigma^2}\right)} = u_2(\gamma_0, \gamma_1) \quad (32)$$

As a result, the maximum capacity under the TIFR transmission policy is given by

$$C_{TIFR} = \max_{\gamma_0, \gamma_1} \left\{ \log\left(1 + \frac{\min\{u_1(\gamma_1), u_2(\gamma_0, \gamma_1)\}}{\sigma^2}\right) \cdot (1 - \overline{K_0} + \overline{K_0} \exp(-\frac{\gamma_0}{\sigma^2}) - \frac{\overline{K_1} \sigma^2}{\gamma_1 + \sigma^2}) \right\} \quad (33)$$

where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$  and  $\gamma_1$ .

For a target outage probability the outage capacity is finally given by:

$$C_{out} = \max_{\gamma_0} \left\{ \log\left(1 + \frac{\min\{\overline{u_1}(\gamma_0), \overline{u_2}(\gamma_0)\}}{\sigma^2}\right) \cdot (1 - \overline{P_{out}}) \right\} \quad (34)$$

where the maximum can be obtained by searching numerically for the optimal value of  $\gamma_0$ .

### Outage Capacity under Both Average and Peak Interference Power Constraints with High Target Detection Probability

In this last subsection, we consider a similar scenario to one in the previous subsection, only this time under joint average and peak interference power constraints on the secondary transmitter. The aforementioned constraints can be expressed as follows:

$$E_{g,h}\{P(H_1)(\overline{P_d})hP_1(g, h) \leq \Gamma \quad (35)$$

$$P(H_1)\overline{P_d}hP_1(g, h) \leq Q_{peak} \quad (36)$$

The parameter  $\alpha$  should satisfy the following constraints:

$$\alpha = \frac{\Gamma}{P(H_1)(\overline{P_d})[\log\left(1 + \frac{\gamma_1}{\sigma^2}\right) - \frac{\gamma_1}{\gamma_1 + \sigma^2}]} = w_1(\gamma_1) \quad (37)$$

$$\alpha \leq \frac{Q_{peak}\sigma^2}{P(H_1)(\overline{P_d})\gamma_1} = w_2(\gamma_1) \quad (38)$$

Therefore, the maximum capacity under the TIFR transmission policy for this case is given by

$$C_{TIFR} = \max_{\gamma_1} \left\{ \log\left(1 + \frac{\min\{w_1(\gamma_1), w_2(\gamma_1)\}}{\sigma^2}\right) \cdot (1 - \overline{K_0} + \overline{K_0} \exp(-\frac{\gamma_0}{\sigma^2}) - \frac{\overline{K_1} \sigma^2}{\gamma_1 + \sigma^2}) \right\} \quad (39)$$

This result can be easily explained by the fact that the secondary user under the imposed constraints can transmit using infinite power; as seen from (37) and (38), for  $\gamma_1 \rightarrow 0$ . For this reason, we choose to apply an (additional) average transmit power constraint as follows:

The maximum capacity under the TIFR transmission policy is now given by

$$C_{TIFR} = \max_{\gamma_0, \gamma_1} \left\{ (1 - P_{out}(\gamma_0, \gamma_1)) \cdot \log\left(1 + \frac{\min\{w_1(\gamma_1), w_2(\gamma_1), w_3(\gamma_0, \gamma_1)\}}{\sigma^2}\right) \right\} \quad (40)$$

and the respective outage capacity for a target probability of outage  $P_{out}$  by

$$C_{out} = \max_{\gamma_0, \gamma_1} \left\{ (1 - P_{out}(\gamma_0, \gamma_1)) \cdot \log \left( 1 + \frac{\min\{w_1(\gamma_1), w_2(\gamma_1), w_3(\gamma_0, \gamma_1)\}}{\sigma^2} \right) \right\} \quad (31)$$

## SIMULATION RESULTS

The figure below is a snap shot of network animator showing spectrum sensing and data transmission done by a secondary simultaneously.

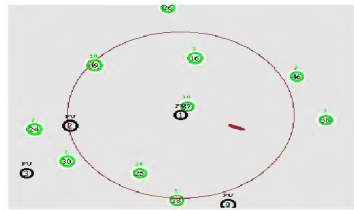


Figure 4

The graph shown below is the analysis of throughput versus transmission power for both conventional and proposed method. We know that in conventional method data transmission is done only after sensing the spectrum hence is throughput is less as compared to the proposed method in which spectrum sensing and data transmission is done at the same time.

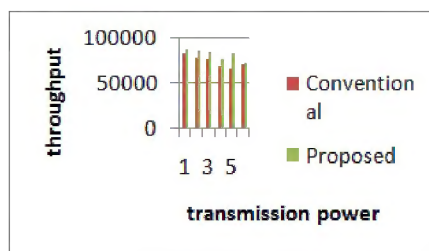


Figure 5

The figure below is a snap shot of network animator showing spectrum sensing and data transmission done by a secondary simultaneously.



Figure 6

The graph shown below is the analysis of throughput versus transmission power for both conventional and proposed method. We know that in conventional method data transmission is done only after sensing the spectrum hence is throughput is less as compared to the proposed method in which spectrum sensing and data transmission is done at the same time.

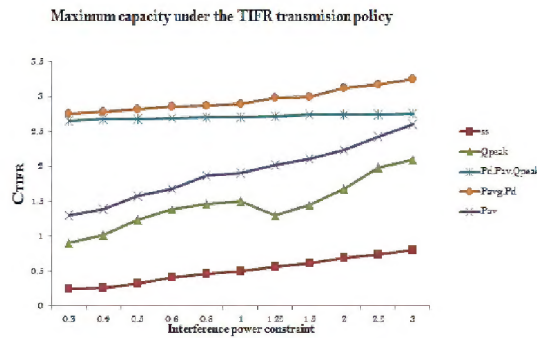


Figure 7

The figure below is a snap shot of network animator showing spectrum sensing and data transmission done by a secondary simultaneously.

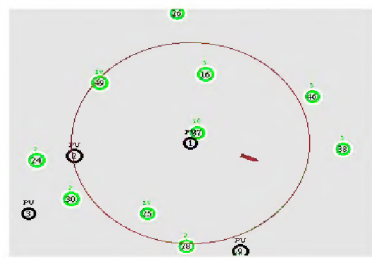


Figure 8

In the graph the maximum capacity of the proposed and the conventional spectrum sharing scheme are presented versus the maximum average interference power  $\Gamma$  is shown. The  $C_{out}$  capacity of the proposed spectrum sharing scheme is presented for the four cases studied in Section 4. These are distinguished in figure below by the applied constraints which are denoted by  $\Gamma$  for the average interference power constraint,  $P_{av}$  for the average transmit power constraint,  $Q_{peak}$  for the peak interference power constraint, and  $P_d$  for the high target detection probability constraint.

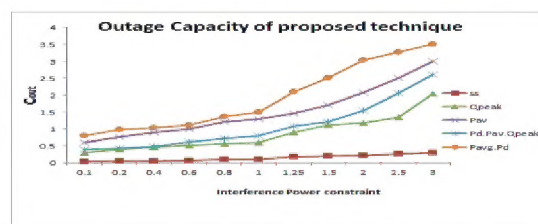


Figure 9

## CONCLUSIONS

Thus in this paper, we emphasised on throughput maximization of spectrum sharing cognitive radio networks and proposed an innovative cognitive radio system that significantly improves throughput more specifically, a novel receiver and a frame structure for spectrum sharing is also being introduced. The problem of optimal power allocation strategy that maximizes the ergodic capacity of the system under average transmit and interference power constraints is studied along with the problem of optimal power allocation strategy that maximizes the outage capacity of the system under average transmit, peak interference and interference power constraints is also studied.

## REFERENCES

1. Fed. Commun. Comm., “Spectrum Policy Task Force Report,” Washington, DC, 02-155, Nov. 2002.
2. J. Mitola, III and G. Q. Maguire, Jr., “Cognitive radios: Making software radio more personal,” *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Aug. 1999.
3. S. Haykin, “Cognitive radio: Brain-empowered wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.
4. Fed. Commun. Comm., “Second Report and Order,” Washington, DC, 08-260, Nov. 2008.
5. Q. Zhao and A. Swami, “A decision-theoretic framework for opportunistic spectrum access,” *IEEE Wireless Commun. Mag.*, vol. 14, no. 4, pp. 14–20, Aug. 2007.
6. A. Ghasemi and E. S. Sousa, “Fundamental limits of spectrum sharing in fading environments,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 2, pp. 649–658, Feb. 2007.
7. M. Gastpar, “On capacity under receive and spatial spectrum-sharing constraints,” *IEEE Trans. Inf. Theory*, vol. 53, no. 2, pp. 471–487, Feb. 2007.
8. X. Kang, Y.-C. Liang, H. K. Garg, and L. Zhang, “Sensing-based spectrum sharing in cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 4649–4654, Oct. 2009.
9. S. Stotas and A. Nallanathan, “Optimal sensing time and power allocation in multiband cognitive radio networks,” *IEEE Trans. Commun.*, vol. 59, no. 1, pp. 226–235, Jan. 2011.
10. Y. C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang, “Sensing-throughput tradeoff for cognitive radio networks,” *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008.
11. L. Musavian and S. Aïssa, “Ergodic and outage capacities of spectrum-sharing systems in fading channels,” in *Proc. IEEE GLOBECOM*, Washington, DC, Nov. 2007, pp. 3327–3331.
12. X. Kang, Y.-C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, “Optimal power allocation for fading channels in cognitive radio networks: Ergodic capacity and outage capacity,” *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 940–950, Feb. 2009.
13. R. Zhang, X. Kang, and Y.-C. Liang, “Protecting primary users in cognitive radio networks: Peak or average interference power constraint?” *Proc. IEEE ICC*, Dresden, Germany, Jun. 2009.
14. J. Lundén, V. Koivunen, A. Huttunen, and H. V. Poor, “Spectrum sensing in cognitive radios based on multiple cyclic frequencies,” in *Proc. Int. Conf. CrownCom*, Orlando, FL, Aug. 2007, pp. 37–43.
15. T. J. Lim, R. Zhang, Y. C. Liang, and Y. Zeng, “GLRT-based spectrum sensing for cognitive radio,” in *Proc. IEEE GLOBECOM*, New Orleans, LA, Dec. 2008.
16. Y. Zeng and Y.-C. Liang, “Spectrum-sensing algorithms for cognitive radio based on statistical covariances,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1804–1815, May 2009.

17. Y. Chen, V. K. N. Lau, S. Zhang, and P. Ciu, "Protocol design and stability/delay analysis of half-duplex buffered cognitive relay systems," *IEEE Trans. Wireless Commun.*, vol. 9, no. 3, pp. 898–902, Mar. 2010.
18. R. Zhang, "On peak versus average interference power constraints for protecting primary users in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 2112–2120, Apr. 2009.
19. D. P. Palomar and M. Chiang, "A tutorial on decomposition methods for network utility maximization," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 8, pp. 1439–1451, Aug. 2006.
20. J. G. Proakis and M. Salehi, *Digital Communications*, 5th ed. New York: McGraw-Hill, 2008.
21. A. J. Goldsmith and P. P. Varaiya, "Capacity of fading channels with channel-side information," *IEEE Trans. Inf. Theory*, vol. 43, no. 6, pp. 1986–1992, Nov. 1997.
22. I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed. New York: Academic, 2007.
23. Z. Quan, S. J. Shellhammer, W. Zhang, and A. H. Sayed, "Spectrum sensing by cognitive radios at very low SNR," in *Proc. IEEE GLOBECOM*, Honolulu, HI, Dec. 2009.